Università degli Studi di Trieste

Dipartimento di Fisica, Sezione di Astronomia

The Effects of Galactic Fountains on the Chemical Evolution of the Milky Way

Emanuele Spitoni

In collaboration with:

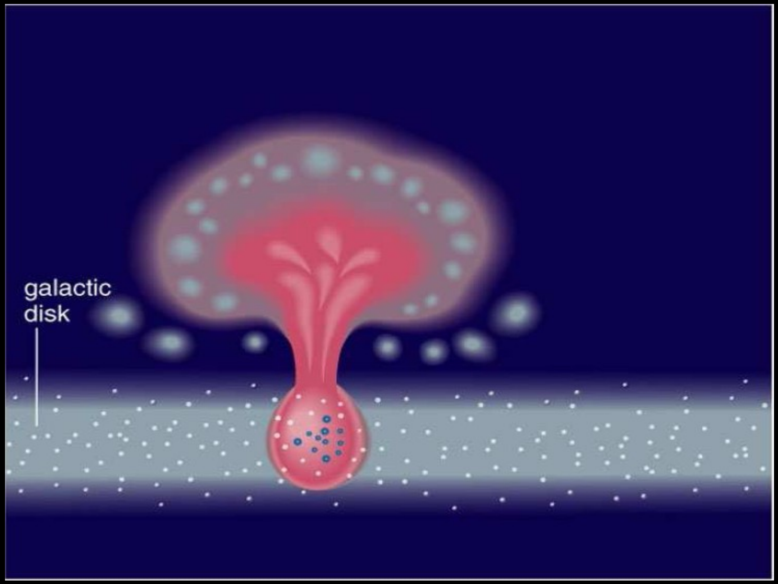
Francesca Matteucci
Simone Recchi

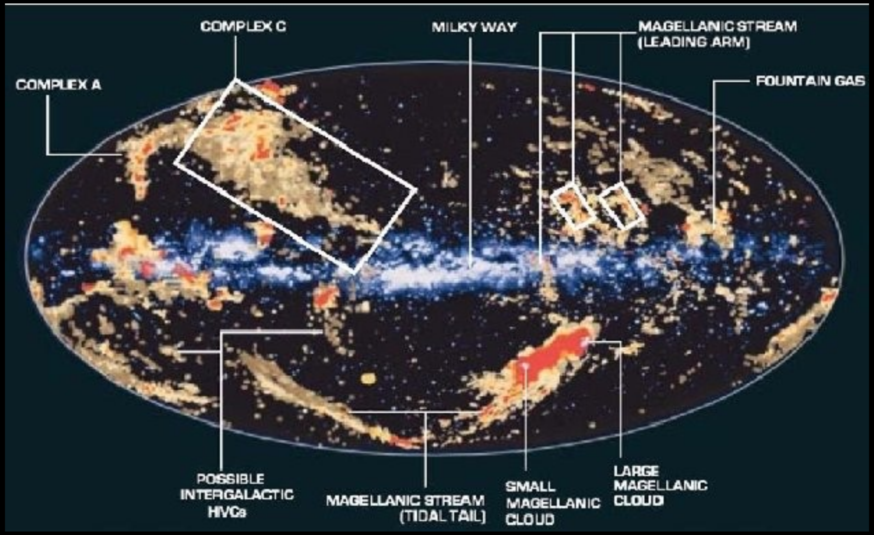
Cosmic Chemical Evolution, St. Michaels, June 3, 2010

Outline

- The galactic fountains: an overview
- Galactic fountains and their connection with HVCs and IVCs
  - The superbubble evolution: the Kompaneets approximation
  - Abundances of Fe and O in the superbubble
  - Comparison with HVC and IVC observations
- Chemical evolution models:
  - A detailed chemical evolution model for the MW
- Effects of Galactic Fountains on the chemical evolution of the MW
- Summary

The Galactic fountain: an overview





(Gouveia Dal Pino et al. 2008)

- Sequential explosions of SNe from an OB association create a superbubble.

- An observed feature which seems to be correlated to gas circulation in galactic fountains are the so-called intermediate and high-velocity-clouds (IVCs and HVCs, respectively).

Galactic fountains and their connection with high and intermediate velocity clouds

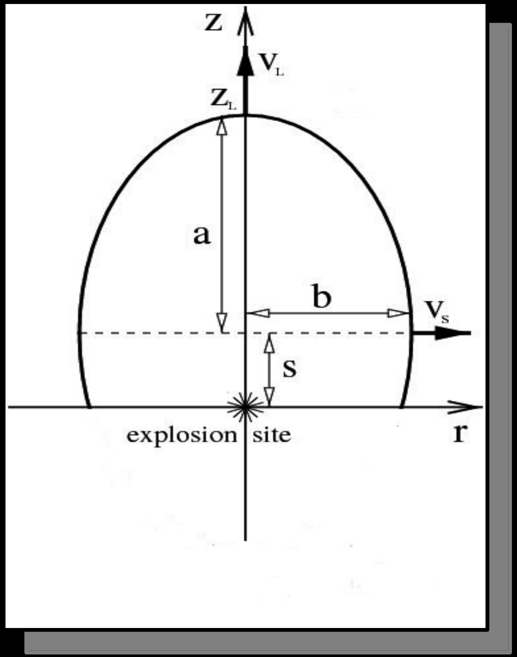
*(**Spitoni, E.**, Recchi, S., Matteucci, F., 2008, A&A, 484, 743)*

The superbubble evolution: the Kompaneets (1960) approximation in our model

(an analytic expression)

- Uniform pressure within the superbubble
- Superbubble expansion in a direction normal to the local surface
- Internal pressure dominates the external pressure
- Superbubble expansion in a exponential atmosphere

$$\rho(z) = \rho_0 exp(-z/H),$$



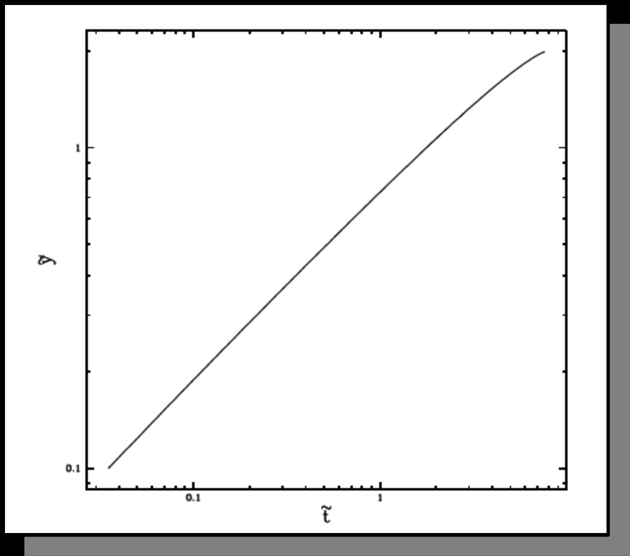
analytic expressions:

for the top side:

$$z_L = -2H \ln\left(1 - \frac{y}{2H}\right)$$

and for the semi-minor axis b:

$$b = 2H \arcsin\left(\frac{y}{2H}\right).$$

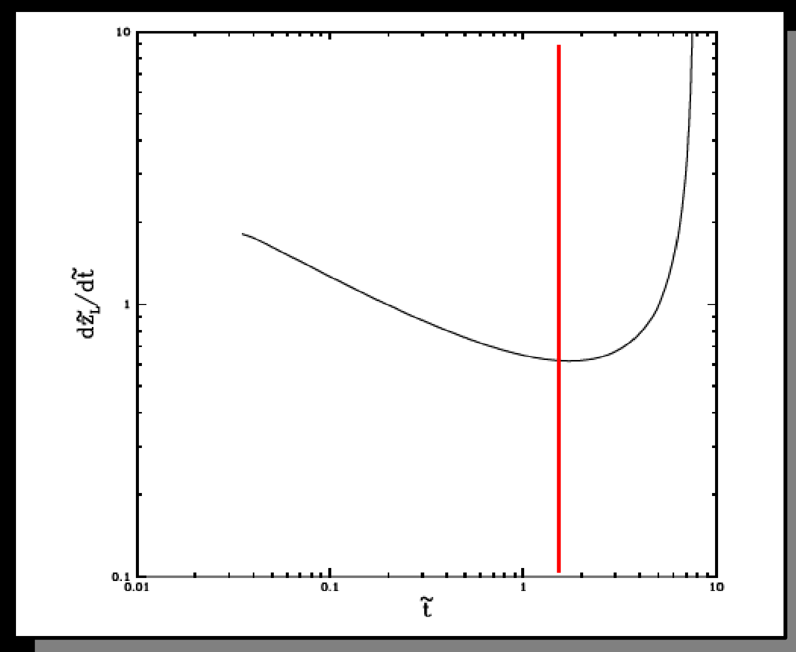


$$y = \int_0^t \sqrt{\frac{\gamma^2 - 1}{2} \frac{E_{\rm th}}{\rho_0 \Omega}}\, dt$$

$$\frac{dE_{th}}{dt} = L_0 - P\frac{d\Omega}{dt}$$

$$P = (\gamma - 1)\, \frac{E_{\rm th}}{\Omega}$$

- There is a typical timescale at which the superbubble "blows up" (e.g. the transition from deceleration to acceleration upwards).



- The most realistic number of massive stars in an OB association is about 100

De Zeeuw et al. (1998)

SNe	L_0 [erg s^{-1}]
10	10^{37}
50	5×10^{37}
100	10^{38}
500	5×10^{38}

$$H = \frac{1}{\rho_0}\int_0^{\infty}\sum_{i=1}^{6}\rho_i(z)\,dz \simeq 141\mathrm{pc}.$$

- Due to the *Raileigh-Taylor instabilities* the supershell fragments and we consider the formation of clouds with an initial velocity given by the top site velocity of the supershell at the moment of fragmentation

- At the time at which the cloud is thrown, the supershell presents:

$z_L = 448$ pc b = 259 pc

($z_L \sim 3H$ in agreement with Mac Low & McCray 1988)

Results: cloud velocities and masses

4 kpc

SNe	t_{final} [yr]	v_n [kms^{-1}]
10	2.289×10^7	23
50	1.339×10^7	39
100	1.063×10^7	49
500	6.2141×10^6	83

8 kpc

SNe	t_{final} [yr]	v_n [kms^{-1}]
10	1.904×10^7	27
50	1.113×10^7	46
100	8.836×10^6	58
500	5.167×10^6	100

12 kpc

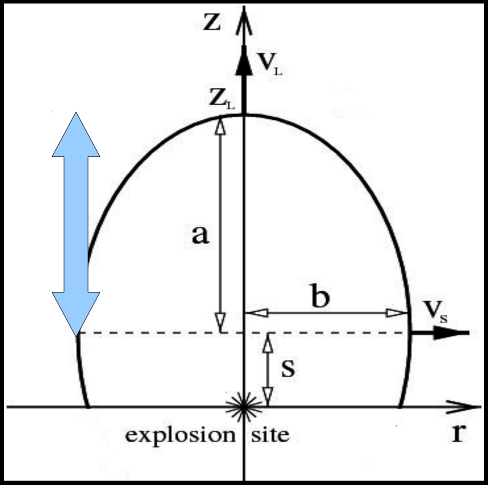
SNe	t_{final} [yr]	v_n [kms^{-1}]
10	1.668×10^7	31
50	9.775×10^6	53
100	7.743×10^6	67
500	4.528×10^6	114

- We assume that the part of the ISM swept up mass into the thin supershell that could fragment and move upwards is the mass included above the *s* height

$$M_{cloud_{R_0=4}} = 2.17\times10^5 M_\odot,$$

$$M_{cloud_{R_0=8}} = 1.24\times10^5 M_\odot,$$

$$M_{cloud_{R_0=12}} = 0.84\times10^5 M_\odot.$$



Abundances of Fe and O in the superbubble

- The mass of metals ejected by SNe is given by: $$M_{el_*} = \int_{M_{inf}}^{40} m_{el}(m)\phi(m)\,dm,$$
  - The lower mass limit corrisponds to the time at which the cloud forms ($M < M_{inf}$ are still alive at the time of cloud formation).
  - IMF Salpeter (1955) $\int_8^{40} \phi(m)\,dm = A\int_8^{40} m^{-2.35}\,dm = SNe$.
  - Yields from Woosley & Weaver (1995) for massive stars.

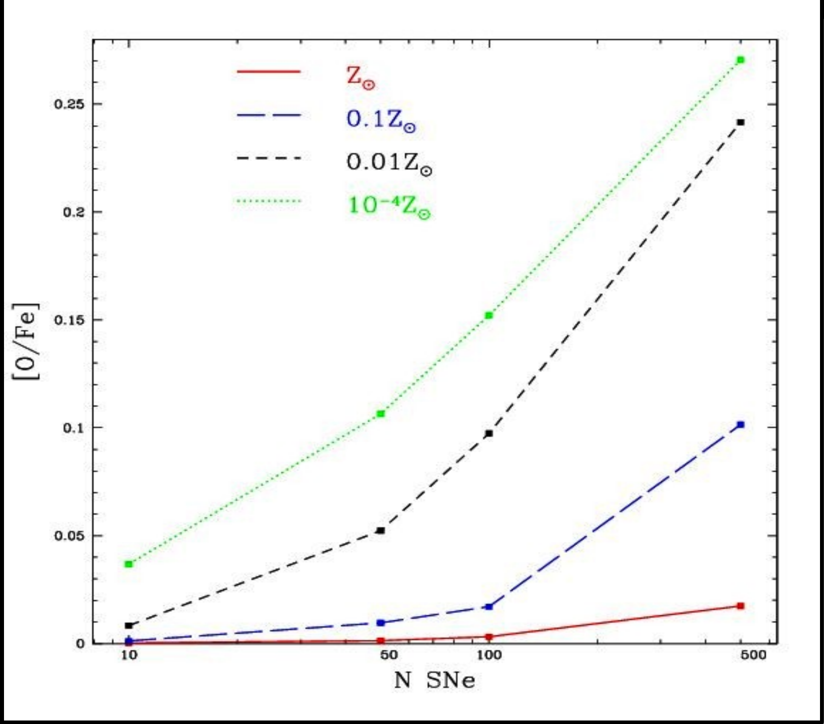
- All the amount of the ejected metals end up in the supershell.

(*an upper-limit estimate*)

$$M_{shell\text{-}el} = M_{shell} * Z_{el} + M_{el*}$$

Stellar yields at 4 different metallicities with the assumption that the ISM in the disk has the same metallicity as the OB association:

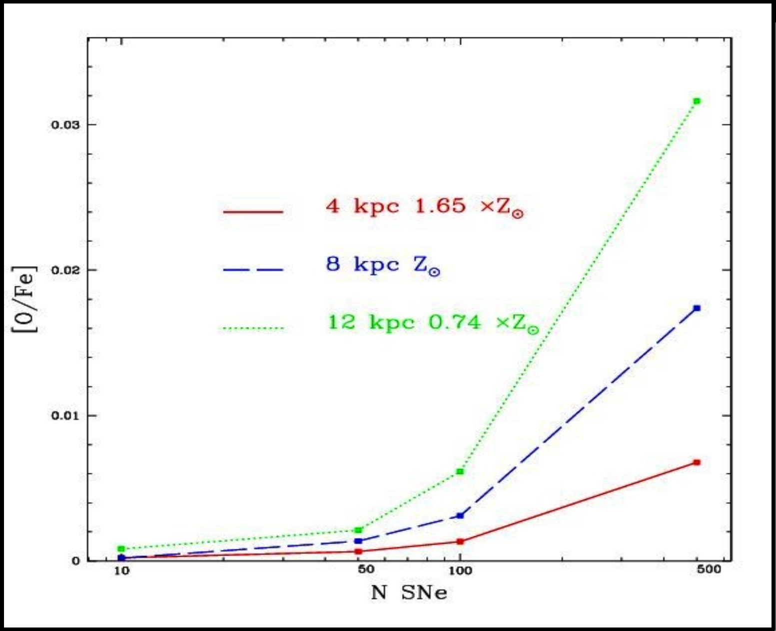
$Z_\odot$ $0.1\,Z_\odot$ $0.01\,Z_\odot$ $10^{4}\,Z_\odot$



$$[O/Fe] = \log\left(\frac{M_{ShellO_{16}}}{M_{ShellFe_{56}}}\right) - \log\left(\frac{O_{16_\odot}}{Fe_{56_\odot}}\right)$$

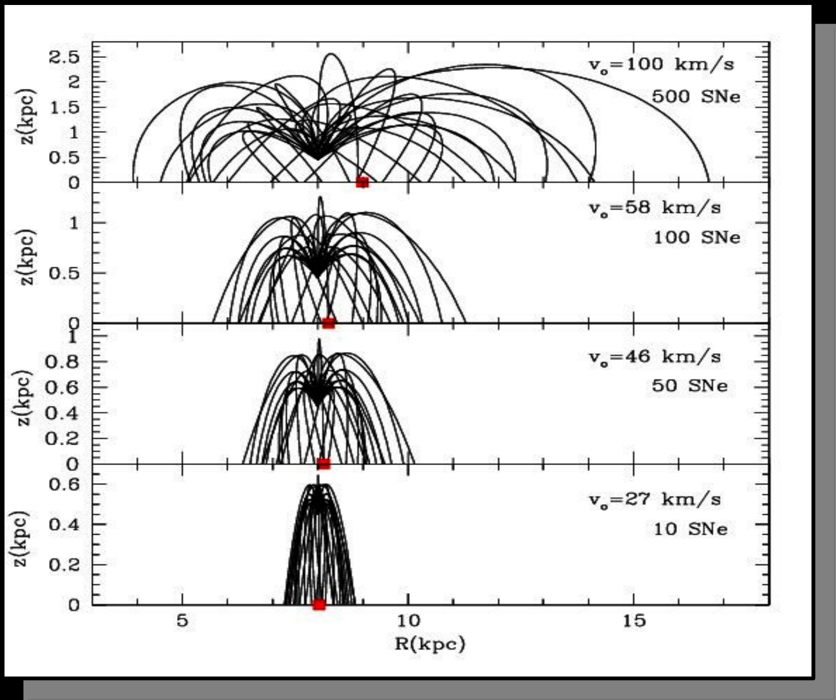
- Significant overbundances of *O* relative to *Fe* are found only in case of a large number of SNe and low initial metallicity (8 kpc).

- For the ISM metallicities we used the average observed values as a function of galactocentric distance, by analysing Galactic Cepheids (Andrievsky et al. 2002; Cescutti et al. 2006).



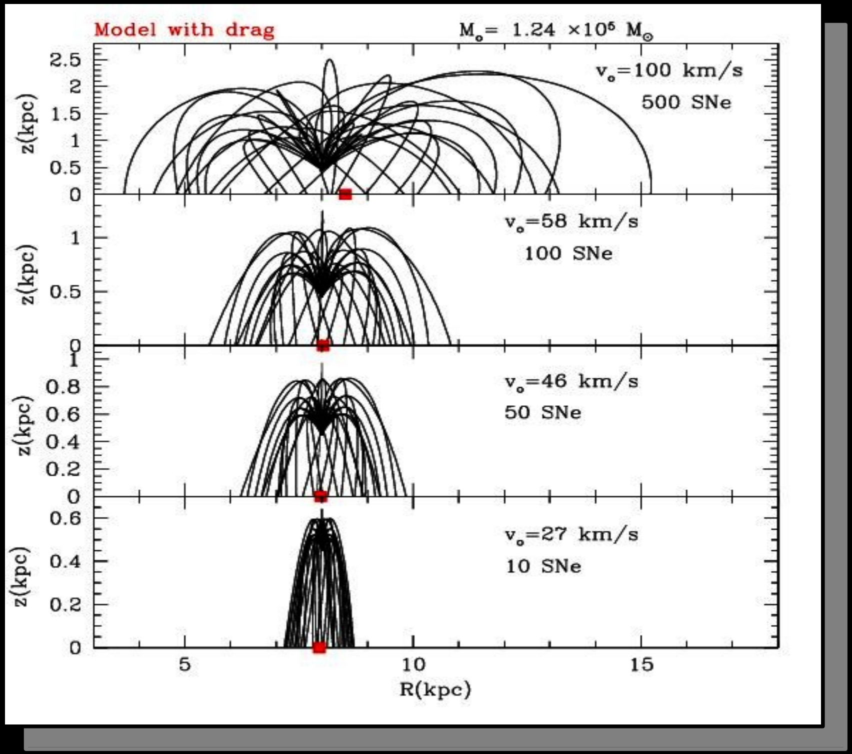
Calculation of the orbits of the clouds

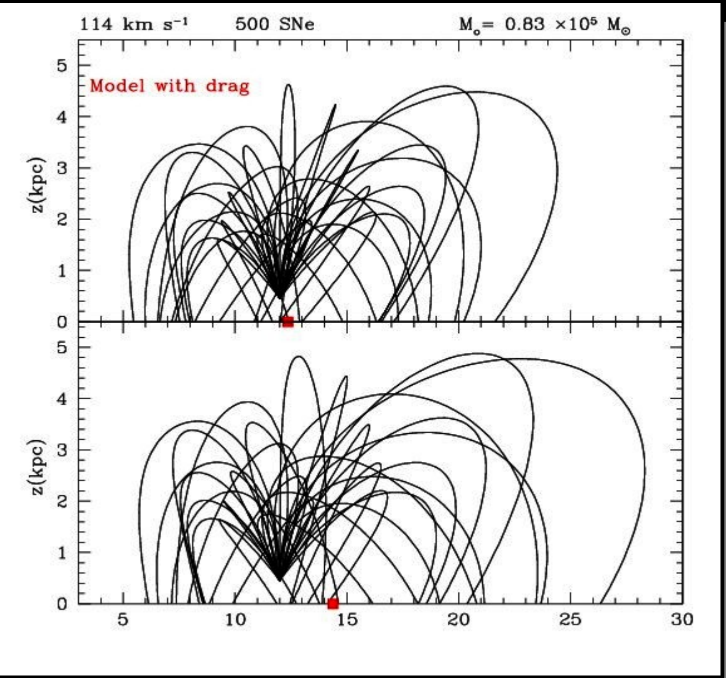
- *Ballistic models:* clouds subject only to the potential of the Galaxy.
- *Hybrid ballistic-fluid stationary model* the clouds are subject also to the viscous interaction with the extra-planar gas.
- The clouds have different initial velocity modulus and masses depending on the the number of SNe in the OB association and the initial throwing radial coordinate.
- The direction of throwing cannot be known a priori: for each velocity modulus v_n we calculated a fountain composed of 33 different direction of throwing.



- The clouds are preferentially thrown outwards, but their final average landing coordinates differ by **1 kpc** at most from the throwing coordinate.

- For the range of initial velocities considered, the effect of a viscous term in the motion equation is weak.





- Fountains that reach the maximum height in our model.

Estimate of the Galactic fountain delay

Everage times necessary to create a cloud + the time for the cloud to fall back onto the Galactic disk (in Myr) .

	4 kpc	8 kpc	12 kpc
10 SNe	43	53	75
50 SNe	36	54	87
100 SNe	36	57	96
500 SNe	38	75	133

	4 kpc	8 kpc	12 kpc
Maximum delay	48 Myr	114 Myr	245 Myr

Comparison with HVC and IVC observations

(data: Wakker et al. 2007, Richter et al. 2001)

Observations

Complex C (HVC)	IV Arch (IVC)
Mass: 0.7 -6 * 10^6 $M_\odot$ Velocity: -114 km s^{-1} Position: R<14 kpc, z=3-9 kpc [*O/Fe*]=0.12 dex	z-height bracket 0.8-1.5 kpc (probably as part of a Galactic fountain) [*O/Fe*]=0.22 dex

Our models

Maximum Mass: 2.* 10^5 $M_\odot$ Maximum Height: 4.4 kpc 500 SN, 12 kpc and Z=0.1*$Z_\odot$: [O/Fe]=0.13 dex. BUT The most likely metallicity at 12 kpc is 0.74*$Z_\odot$: 500 SNe [*O/Fe*]=0.03 dex	Z=0.01 *$Z_\odot$ [*O/Fe*]=0.24 dex, 500 SN 8 kpc

- We can rule out a Galactic origin for the Complex C HVC

- It is quite unlikely that the initial metallicity of an OB association is nowdays as low as 0.01 * $Z_\odot$

Effects of Galactic Fountains on the chemical evolution of the MW

*(**Spitoni, E.**, Matteucci, F., Recchi.S., Cescutti, G., Pipino, A., 2009 A&A, 504, 87)*

- *To take into account the effects of galactic fountains we consider a delay in the chemical enrichment of the MW (the relaxation of the IMA)*

    - Most of the chemical evolution models adopt the IMA. In the past there have been only a few attempts to relax the IMA because of:

        - Difficulties in estimating the dispersion time and mixing of the chemical elements (Roy & Kunth 1995)

        - Models which retain IMA provide an excellent fit of the data in the MW (François et al. 2004)

The detailed two infall chemical evolution model

(an upgrade of the original two-infall model of Chiappini et al. 1997 updated by Francois et 2004 and Cescutti et al. 2007)

- Two-infall model

$$A(r,t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{max})/\tau_D(r)}$$

- Inside-out formation

$$\tau_D = 1.033r(\mathrm{kpc}) - 1.267\ \mathrm{Gyr}$$

- Threshold in the star formation

SFR ∞ $\sigma_G^{1.5}$

Thin disk phase: if $\sigma_G < 7\ M_{sun}\ pc^{-2}$

SFR=0

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t)$$

$$+\int_{M_L}^{M_{Bm}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+A_{Ia}\int_{M_{Bm}}^{M_{BM}} \phi(M_B)\cdot\left[\int_{\mu_m}^{0.5} f(\mu)\psi(r,t-\tau_{m2})Q_{mi}^{SNIa}(t-\tau_{m2})d\mu\right]dM_B$$

$$+(1-A_{Ia})\int_{M_{Bm}}^{M_{BM}} \psi(r,t-\tau_m - \Delta t_1)Q_{mi}(t-\tau_m - \Delta t_1)\phi(m)dm$$

$$+\int_{M_{BM}}^{M_U} \psi(r,t-\tau_m - \Delta t_1)Q_{mi}(t-\tau_m - \Delta t_1)\phi(m)dm$$

$$+X_{A_i}A(r,t)$$

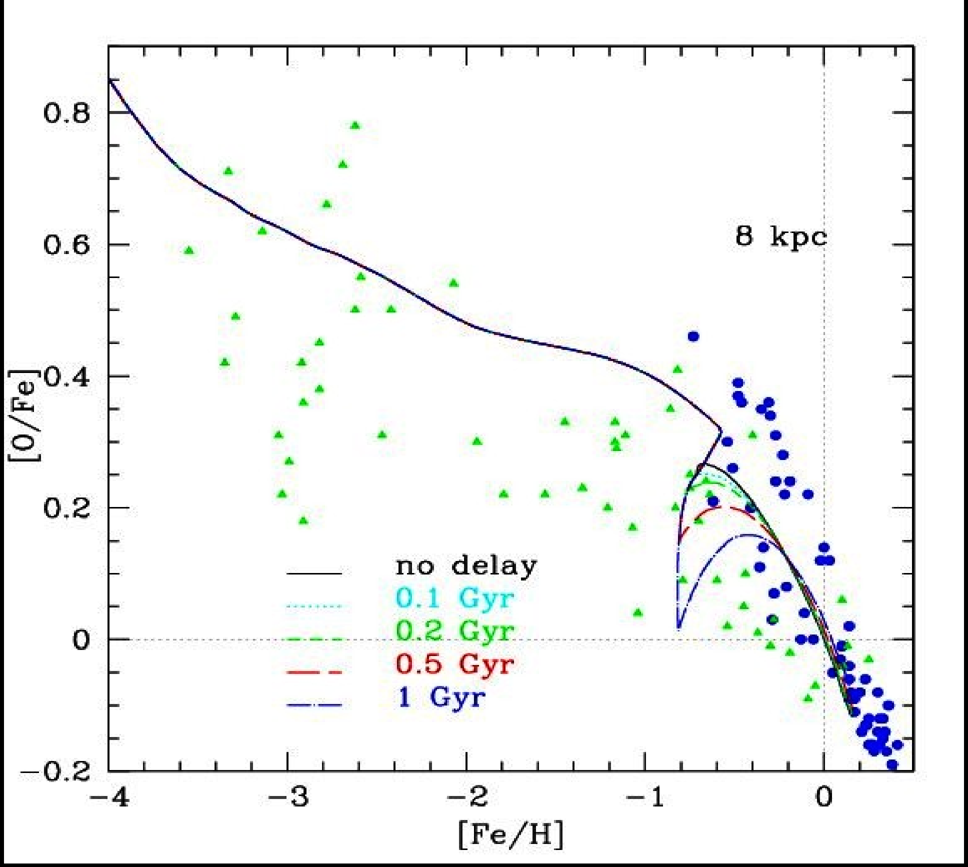
Description of the Galactic fountain delay model

- We considered the delay only for massive stars $M > 8\ M_{\odot}$.
- We computed this effect only on thin disk stars (e. g. only for stars born after the halo-thick disk transition) because the “break out” event, necessary for a galactic fountain, requires that the OB association sit on a *plane stratified disk* where the density decreases along the z-axys.
- Time delay: 0.1, 0.2, 0.5, 1.0 Gyr (… a delay of 1.0 Gyr can be obtained in case of a OB association composed by 10^4 SNe).

Results

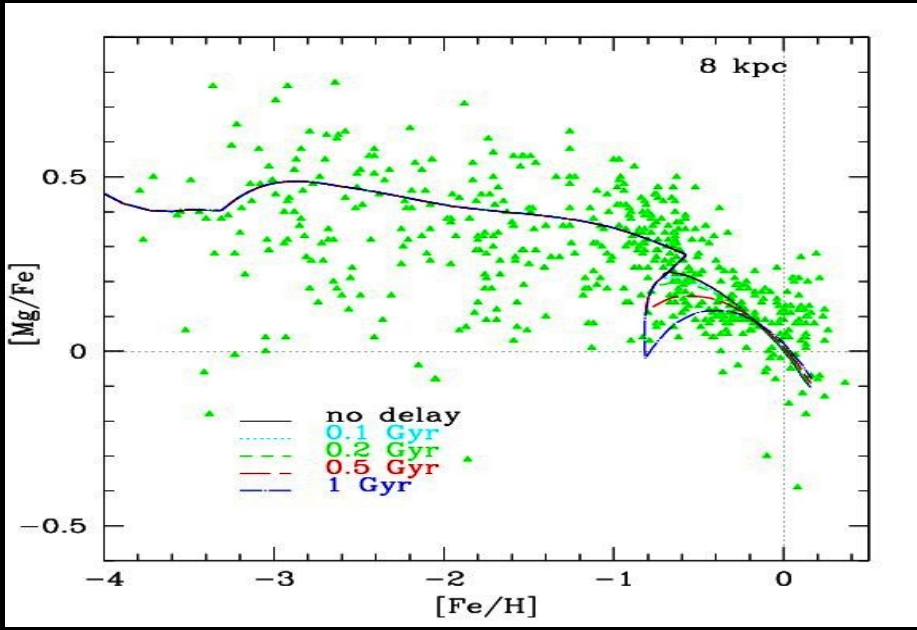
8 kpc

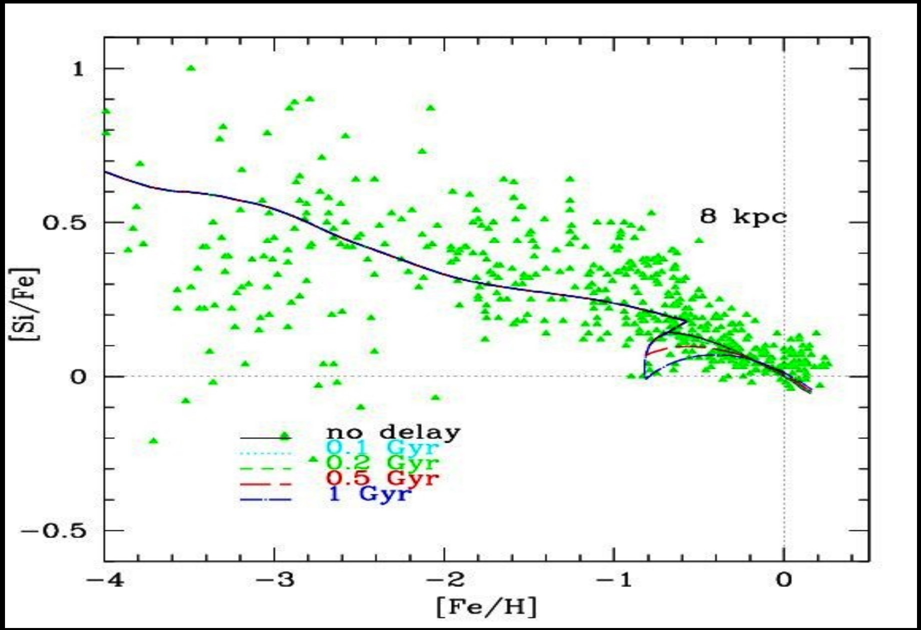
[el/Fe]/ [Fe/H]



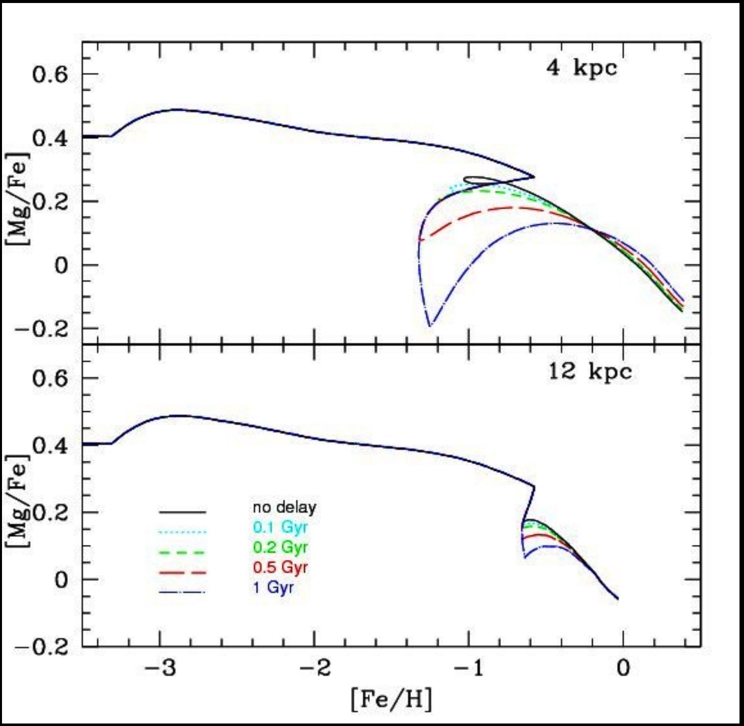
Data: Bensby (2004), François et al. (2004)

- The main feature of the galactic fountain is an enhancement of the drop in the [O/Fe] ratio. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- Type Ia SNe are not affected by the delay
- The maximum possible delay must be lower than 1.0 Gyr



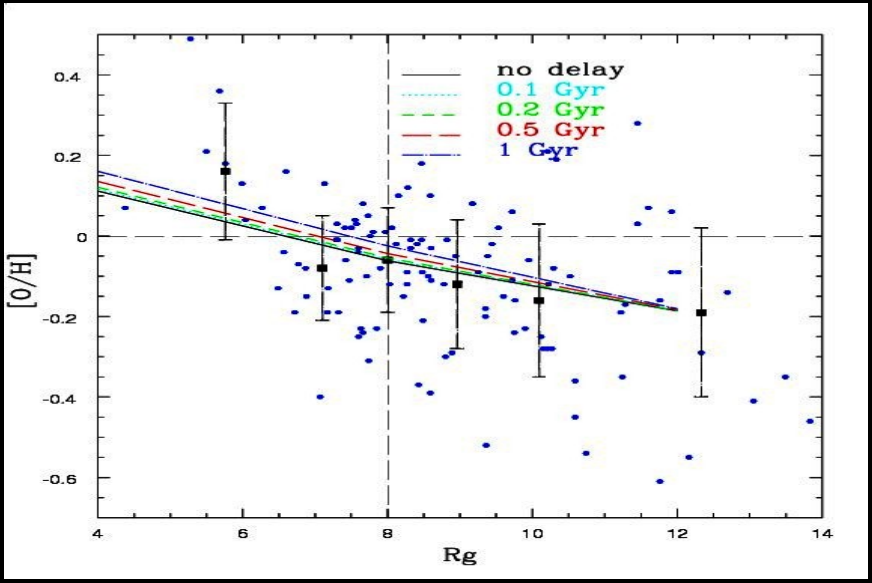


- The effect of the galactic fountain depends on the considered element. Si, which is also produced by type Ia SNe in a non negligible amount, shows a smaller drop of the [Si/Fe] quantity compared to O and Mg.



- The effect depends on the galactocentric distance: different histories of star formation at different galactocentric radii

- The time delay produced by a galactic fountain has a negligible effect on the abundance gradient in the Galaxy disk



Data from Andriesky et al. (2002)

Summary

- If the initial metallicity of the OB association is solar, the pollution from the dying stars has a negligible effect on the chemical composition of the clouds.
- Both in the ballistic and in the viscous interaction models the maximum height reached by the clouds is not very large.
- The clouds are generally directed outwards but the average landing coordinates differ from the throwing coordinates by 1 kpc at most therefore it is unlikely that galactic fountains affect abundance gradients .
- It is unlikely that the two studied clouds are originated in a Galactic fountain motion.
- We showed that in the solar neighbourhood the delay produced by a galactic fountain has a negligible effect on the chemical evolution of all α elements we studied.
- In [el/Fe] versus [Fe/H] relations, the main feature of the galactic fountain is an enhancement of the drop in the [el/Fe] ratios. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- *The time delay produced by a galactic fountain originated by an OB association has a negligible effect on the abundance gradients in the Galaxy disk.*